Pion Transparency in 500 MeV $C(\pi,\pi^{'})$ Reactions?

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The question whether there is a pion transparency in 500 MeV $C(\pi,\pi^{'})$ scatterings is studied using a semiclassical, hadronic transport model. The double differential cross sections of this reaction measured at LAMPF can be largely accounted for, if one uses energy-dependent, anisotropic angular distributions which are fitted to pion-nucleon scattering data for the decay of $\Delta(1232)$ and $N^*(1440)$ resonances. The remaining discrepancy between the data and the calculation sets a limit on effects of more exotic processes.

Pion−nucleus scatterings at energies near the peak of $\Delta(1232)$ formation ($T_\pi \approx 180$ MeV) have been studied extensively at several meson facilities during the last two decades. Experiments at LAMPF, KEK and BNL using high energy pions far above the resonance peak have recently started to accumulate interesting data [1–4]. Since the pion−nucleon cross section decreases by almost an order of magnitude as the pion energy increases from the resonance energy to higher energies, high energy pions are therefore expected to penetrate more deeply into the interior of nuclei. To understand the dynamics of these high energy pions in nuclear matter is one of the major goals of current experimental studies on pion−nucleus scatterings. These studies will be further enhanced by the availability of pion beams at GSI/Darmstadt, Germany in the near future.

Among these studies, one interesting phenomenon was recently found at LAMPF in inclusive scatterings of 500 MeV pions from a carbon target [2]. The (π, π') inclusive cross sections, with outgoing pion energies near 200 MeV, failed to show the strong depletion predicted by an intranuclear cascade model (INC) [5]. To bring the INC prediction close to the data requires that pions from the $(\pi, 2\pi)$ channel do not interact with the nucleus for about 2 fm/c. As an alternative mechanism for filling up this dip, the possibility of forming a σ meson was also suggested. Since the isospin zero character of the σ prevents it from interacting strongly with the nucleus, it will mainly decay into two pions outside the nucleus. Both mechanisms thus require that the nuclear medium is transparent to pions that are from the $(\pi, 2\pi)$ production channel. It is also interesting to mention that the Relativistic Quantum Molecular Dynamics (RQMD 1.08) has been used as well to understand the data [6]. However, it underestimates the data at forward angles by a factor of 2-7 in the whole energy range. At large angles, it overestimates the data by a factor of 2-6 for energy losses between 200 and 300 MeV and underestimates significantly other parts of the spectra. The discrepancies between the data and the model predictions, as well as the different mechanisms proposed to explain them, have attracted much attention and stimulated many interesting discussions. This problem was assigned to several participants as a homework by the organizers of the workshop on “pionic processes and transport in hadronic matter” at

Los Alamos in July, 1995 [7]. In this Letter we report results of our study using a hadronic transport model BUU/ART [8,9].

The BUU/ART model has been used successfully in studying many aspects of heavy-ion collisions from low to relativistic energies, especially the pion observables (e.g. [10]). Since pions are the most copiously produced particles in relativistic heavy-ion collisions, it is crucial to understand very well their transport dynamics in nuclear matter. In this respect pion−nucleus collisions provide a clean testing ground. It is therefore interesting to test models for heavy-ion collisions against data from pion−nucleus collisions. In fact, a wealth of interesting physics on the propagation of pions has been extracted from pion−nucleus scatterings during the last two decades. In the present letter, we have incorporated most of these effects into our semiclassical transport model in order to compare with the recent data from pion induced reactions.

Three aspects of the BUU/ART model, pion-scattering, -production and -absorption, are important for studying pion−nucleus interactions. In this model, pion scatterings are modeled through the formation and decay of $\Delta(1232)$ and $N^*(1440)$ resonances. Although these resonances should decay in definite angular momentum channels (P_{33} and P_{11}), in heavy-ion collisions it is customary to assume that baryon resonances decay isotropically in their center of mass frames since frequent rescatterings of these resonances in dense hadronic matter largely smear out information about the angular distribution from their decays. For describing pion−nucleus scatterings, however, it is important to incorporate properly experimentally measured angular distributions in pion− nucleon scatterings. These distributions were found to be strongly energy dependent [11]. More specifically, the distribution is about forward-backward symmetric only at center of mass energies near the peak of the delta resonance (1232 MeV) due to P-wave dominance. It is strongly backward peaked at lower energies, and forward peaked at higher energies due to the contribution and interference of many partial waves. Within the present model our classical treatment has no way of reproducing naturally the interference and thus the experimental angular distribution. To evaluate effects of the pion−nucleon angular distribution on pion double differential cross

sections in pion− nucleus scatterings, we will compare two extreme cases by forcing the resonances to decay either isotropically or according to the measured pion−nucleon angular distributions. It is worth mentioning that our treatment here is rather similar in spirit to those of the early INC models for pion induced reactions [12,13].

The measured pion−nucleon angular distribution in their center of mass frame can be expressed in terms of Legendre polynomials frame [14,15]

$$\frac{d\sigma}{d\Omega^*} = \sum_{n=0}^{n_{max}} c_n P_n(cos\theta^*). \tag{1}$$

The coefficients c_n at different energies are listed in ref. [11] for $\pi^{\pm}p$ scatterings. We use proper Clebsch-Gordon coefficients to obtain the angular distributions for the decay of resonances with different charges. Shown in Fig. 1 are the angular distributions for the decay of Δ^{++} resonances having masses of 1.1, 1.23, 1.5 and 1.8 GeV.

At $T_\pi = 500$ MeV the total $\pi + N$ inelastic cross section results almost completely from the production of two pions [16], $\pi + N \to 2\pi + N$. We model this process by using the reactions $\pi + N \to \pi + \Delta$ and $\pi + N \to \rho + N$. Assuming the formation of higher resonances (Δ^* and N^*) in the intermediate state [9], the branching ratio of the two channels can be estimated according to

$$\frac{\sigma(\pi + N \to \pi + \Delta)}{\sigma(\pi + N \to \rho + N)} = \frac{\sum_i (2J_i + 1)\Gamma_i(R_i \to \pi\Delta)W(R_i)}{\sum_i (2J_i + 1)\Gamma_i(R_i \to \rho N)W(R_i)}, \tag{2}$$

which is about a constant of 1.7 for $1.22 \leq \sqrt{s_{\pi N}} \leq 1.66$ GeV. In the above, R_i are the higher Δ^* and N^* resonances with masses up to 1.7 GeV, $\Gamma_i(R_i \to \pi\Delta(\rho N)$ are the partial decay widths of these resonances and

$$W(R_i) = \frac{m_i^2 \Gamma(\pi N \to R_i)}{(m_i^2 - s)^2 + m_i^2 \Gamma^2(\pi N \to R_i)} \tag{3}$$

is the Breit-Wigner formula for the formation of these resonances.

Pion absorption is modeled through either the two-step, two-body processes $\pi + N \to \Delta(N^*)$ and $\Delta(N^*) + N \to N + N$ or the quasi-deuteron absorption processes $\pi + D \to NN$. Parameters used for the two-body, two-step processes have been discussed in detail in ref. [8]. For the quasi-deuteron process $\pi^+ + np \to pp$ we use the experimental cross section [17]

$$\sigma(\pi^+ + np \to pp) = \frac{b}{\sqrt{T_\pi}} + \frac{c}{(\sqrt{s_{\pi np}} - E_R)^2 + d} + a; \tag{4}$$

with $a = -1.2$ mb, $b = 3.5$ mb MeV$^{-1/2}$, $c = 7.4 \cdot 10^4$ mb MeV^{-2}, $d = 5600$ MeV^2 and $E_R = 2136$ MeV. In the above $\sqrt{s_{\pi np}}$ is the center of mass energy of the $\pi - D$ system. The quasi-deuteron is identified as two nearest nucleons with a maximum separation of 3 fm and proper charges to match the pion. Cross sections for pion absorptions on other quasi-deuterons are obtained via [18]

$$\sigma(\pi^- np \to nn) = \sigma(\pi^+ np \to pp), \tag{5}$$

$$\sigma(\pi^0 np \to np) = 0.44 \cdot \sigma(\pi^+ np \to pp), \tag{6}$$

$$\sigma(\pi^0 pp \to pp) = \sigma(\pi^0 nn \to nn) = 0.14 \cdot \sigma(\pi^+ np \to pp), \tag{7}$$

$$\sigma(\pi^+ nn \to np) = \sigma(\pi^- pp \to np) = 0.083 \cdot \sigma(\pi^+ np \to pp). \tag{8}$$

The three terms in Eq. (4) represent respectively contributions to the quasideutron absorption from s-wave, p-wave and higher partial waves as well as the interference among them. The quasideutron absorption process allows us to include the absorption of low energy pions via s-wave properly. It may also introduce some double counting of the p-wave absorption. We estimate, however, that this double counting is very small as the second term in Eq. (4) has a maximum of only about 10 mb which is very small compared to that in the two-body, two-step process. On the other hand, it also seems improper to simply throw away the p-wave contribution in Eq. (4) as our model does not include the interference of different partial waves. To minimize possible double countings of the p-wave absorption we allow a pion and nucleons to participate in only one of the pion absorption channels during each time step. Moreover, the quasi-deutron absorption process is treated explicitly as a one-step process.

In transport model calculations, we need to know the initial distribution of nucleons in the nucleus. For a carbon nucleus, nucleons are initialized using the experimentally measured charge distribution

$$\rho(r)/\rho_0 = (1 + wr^2/c^2)\,(1 + \exp((r-c)/z)) \tag{9}$$

with $c = 2.36$ fm, $z = 0.522$ fm and $w = -0.149$. The momenta of nucleons are assigned using the local Thomas-Fermi approximation.

To test the validity of the transport model, we first perform a study on pion absorption cross sections in pion−nucleus scatterings in a large beam energy range. This study is a prerequiste for us to study the double differential cross sections in the following. We notice that the pion absorption cross sections in pion−nucleus scatterings have been studied in a similar transport model in ref. [18] for various targets. Here we perform a study for $\pi^+ +^{12} C$ reactions at beam energies from 50 to 500 MeV in Fig. 2. The data are taken from ref. [19] (filled circles), ref. [20] (filled squares) and ref. [21] (fancy squares). Results using the "standard" BUU/ART model (i.e. without changes in the elementary cross sections described above, and assuming isotropic decays of resonances in their rest frames) are shown with the open circles. The line is drown to guide the eye. It is seen that the calculations agree reasonably well with the data within error bars.

In Fig. 3 the inclusive double differential spectra from the scattering of 500 MeV π^+ on carbon are shown as a function of the energy loss $(T_{in} - T_{out})$. The symbols with error bars are the data and the lines are from calculations. The results from the "standard" BUU/ART model calculations are given by the dotted lines. First, in contrast to the INC predictions, we do not see the one-order-of-magnitude depletion in cross sections from the data at energy losses around 300 MeV at forward angles. Second, we notice that the calculations underestimate significantly the quasielastic peaks at 30, 40 and 50 degrees, and also overestimate the data at 70, 90 and 110 degrees. Third, the elastic peaks at forward angles corresponding to the recoil of the whole carbon nucleus can not be reproduced by the model as one expects.

We find that the agreement with the data can be much improved by allowing the resonances to decay anisotropically according to Eq. (1). This result is shown by the solid lines. It is fair to say that the quality of fit to the data is at about the same level as the INC calculations [5] using a 2 fm/c formation time for pions from the $(\pi, 2\pi)$ process. From this one might conclude that the evidence for the formation time effects previously reported is not yet conclusive.

It is interesting to see that the improvement due to the anisotropical angular distributions is mainly around the quasielastic peaks. This is because the high energy-loss parts of the spectra are due to pions produced in $(\pi, 2\pi)$ process, which is in agreement with the finding of the INC calculations. We notice that in both the INC and the present model the calculated spectra at 30, 40 and 50 degrees are smaller than the data by about a factor of two in the energy range of $T_{in} - T_{out} \geq 150$ MeV. This discrepancy may be used to limit effects of possible exotic processes. We have not yet tested the possibility of forming the σ meson in the model. On the other hand, we have studied effects of possible enhancement of the in-medium pion−nucleon inelastic cross sections. This is motivated by studies in K^+-nucleus scatterings where the underestimate of theoretical calculations compared to the experimental data has led to the suggestion that the kaon-nucleon cross section is enhanced in the nuclear medium [22–25]. Possible explanations for the increased cross section are the increase in the nucleon's size in medium due to QCD related physics [23], or the scattering from enhanced meson clouds caused by the reduction of meson masses in medium [25]. Since high energy pions have mean free paths compatible to kaons, signatures of these exotic processes were expected to be identifiable in high energy pion−nucleus scatterings, and indeed some indication of the increased in-medium pion−nucleon cross sections has been found in ref. [3]. Here we perform a rather exploratory study in order to set a limit on this exotic process. By simply increasing the pion−nucleon inelastic cross section by a factor of three without changing its branching ratios, we have found that the discrepancy at $T_{in} - T_{out} \geq 150$ MeV can be largely removed. As shown by the dashed lines in Fig. 3, this modification only increases the cross section of produced pions without affecting the quasielastic parts of the spectra. In this respect, it is worthwhile to mention that several theoretical studies (e.g. [26–30]) have shown that the properties of hadrons (e.g. Δ and ρ), such as their masses and decay widths, may be modified in the nuclear medium as a result of the partial restoration of chiral symmetry. The appreciable effect on pion spectra due to increased pion−nucleon cross sections calls for more detailed study on medium effects. More data of high energy pion−nucleus scatterings are thus desirable.

In summary, by using a hadronic transport model originally designed for heavy-ion collisions we have analyzed the double differential cross sections in 500 MeV $C(\pi, \pi^{'})$ scatterings. The data can be largely accounted for if one uses energy-dependent, anisotropic angular distributions that are fitted to pion−nucleon scattering data in the decay of $\Delta(1232)$ and $N^*(1440)$ resonances. We have also found that even with the careful inclusion of all presently known important pion−nucleon processes the semiclassical transport theory is not able to completely reproduce the pion−nucleus scattering data studied here. The disagreement of up to a factor of three in parts of the energy-loss spectra leaves open the possibility that exciting new physics may play a role here.

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FIGURE CAPTIONS

Fig. 1 The angular distribution of pions from the decay of Δ^{++} resonance in its rest frame.

Fig. 2 Pion absorption cross section as a function of beam energy in $\pi^+ + ^{12}C$ scatterings. The data are taken from refs. [19–21]. (see text).

Fig. 3 Inclusive double differential cross sections of pions as a function of the pion laboratory angle and the pion energy loss, $T_{\rm in} - T_{\rm out}$, in 500 MeV $C(\pi^+, \pi^{+'})$ reactions. The data (circles) are from ref. [2].

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